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The LSC-Virgo White Paper on Gravitational Wave Searches and Astrophysics
Executive Summary
(2015-2016 edition)

The LSC-Virgo Data Analysis Council

WWW: http://www.ligo.org/ and http://www.virgo.infn.it

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1 LSC-Virgo Gravitational Wave Searches and Astrophysics

Gravitational wave searches and astrophysics in the LIGO Scientific Collaboration (LSC) and Virgo collaboration are organized by astrophysical source classification into four working groups. The **Compact Binary Coalescence (CBC)** group searches for signals for merging neutron stars or black holes by filtering the data with waveform templates. The **Burst (Burst)** group searches for generic gravitational wave transients with minimal assumption on the source or signal morphology. The **Continuous Waves (CW)** group targets periodic signatures from rotating neutron stars. The **Stochastic (SGWB)** group looks for a gravitational wave background of cosmological or astrophysical origin. Joint teams across two or more working groups exist where the science suggests overlap between sources or methods. In addition, the **Detector Characterization (Detchar)** group collaborates with the detector commissioning teams and works to improve searches by identifying and mitigating noise sources that limit sensitivity to astrophysical signals.

The *LSC-Virgo White Paper on Gravitational Wave Searches and Astrophysics*, which is updated yearly, describes the astrophysical search plans of the LSC-Virgo working groups. This document is its executive summary. For each group, it provides a mission statement and scientific priorities in the Advanced Detector Era, as well as statements from Detector Characterization, Calibration and Hardware Injection teams.

We refer to the Advanced Detector Era (ADE) as the epoch of Advanced LIGO and Advanced Virgo science data acquisition, scheduled to start in the second half of 2015. Table 1 shows the planned schedule of science runs, as provided by the LSC-Virgo Joint Running Plan Committee, which includes representatives from the laboratories, the commissioning teams and search groups.

Epoch	Estimated Run Duration	Run Name	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)		Binary Neutron Star Range (Mpc)		Number of Binary Neutron Star Detections
			LIGO	Virgo	LIGO	Virgo	
2015	3 months	O1	40 – 60	–	40 – 80	–	0.0004 – 3
2016–17	6 months	O2	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20
2017–18	9 months	O3	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100

Table 1: Plausible observing schedule and expected sensitivities with the advanced LIGO and Virgo detectors, which will be strongly dependent on their commissioning progress. The two LIGO detectors meet the minimum requirements for the first “O1" run now. [arXiv:1304.0670]

The LSC-Virgo scientific priorities for ADE observations are summarized in Table 2, by search group, in three categories:

- **Highest priority:** searches most likely to make detections or yield significant astrophysical results.
- **High priority:** promising extensions of the highest priority goals that explore larger regions of parameter space or can further the science potential of LIGO and Virgo.
- **Additional priority:** sources with low detection probability but high scientific payoff.

Computing needs and resource allocations are derived from the science priorities presented in this table. Scientific motivations, details on methods and the strategy for result validation are provided in the search plans that constitute the white paper.

We note that the LSC-Virgo Collaboration has adopted a *Multiple Pipeline Policy* [LIGO-M1500027], which calls for all astrophysical results to be validated with a different analysis, using independent methods and tools when possible. In some cases this may require the same data to be analyzed by more than one pipeline for the same science target.

	Burst	CBC	CW	SGWB
Highest priority	All-sky search for generic GW transients, in low latency for EM followup and deep, offline for 4σ detection confidence	All-sky matched-filter search for binary neutron star (BNS) systems, deep and low latency	All-sky search for isolated neutron stars, both as a *quick-look* on owned resources and as a deep/broad search on Einstein@Home	Directional search for stochastic GW background
	Parameter estimation for the astrophysical interpretation of detected burst events	All-sky matched filter search for binary neutron-star and black-hole (NSBH) systems, deep and low latency	Targeted search for high value, known pulsars	Isotropic search for stochastic GW background
	Search for GW bursts triggered by outstanding GRB alerts	All-sky matched-filter, deep search for binary black-hole (BBH) systems	Directed searches for Cas-A	Constraints of a detected background of astrophysical origin with long transients
	Searches triggered by outstanding astrophysical events (a galactic supernova, neutron star transients, an exceptional high energy neutrino alert)	Parameter estimation of detected CBC events	Directed searches for X-ray binaries SCO-X1 and J1751-305	
	Search for cosmic string kinks and cusps	CBC searches triggered by all GRB alerts		
		Tests of General Relativity with CBC events		
High priority	Searches triggered by high energy neutrinos, extra-galactic supernovae, and GRB observations	All sky search for spinning binary neutron star systems (deep and low latency)	Targeted search for other known pulsars	Long transient follow up of CBC and burst candidates
	Burst search for intermediate mass and eccentric black hole binary systems	Matched filtered search for intermediate mass black hole binary systems	Directed searches for other isolated stars and X-ray binaries	
	All-sky search for long bursts of > 10 s duration			
Additional priority	GRB-triggered search for long-duration bursts and plateaus	Exploring effects of detector noise on parameter estimation	All sky search for isolated stars (alternative approaches)	
	Hypermassive neutron star followup		All-sky search for binaries	
	Burst searches triggered by radio transients and by SGR/SGR-QPO		Spotlight deep sky-patch search **	
	Burst tests of alternative gravity theories **		Search for Supernova post birth signals **	
			Search for continuous wave transients **	

Table 2: Science priorities of the LIGO-Virgo collaboration, for the four astrophysics search groups: Bursts, Compact Binary Coalescences (CBC), Continuous Waves (CW), and Stochastic Gravitational Wave Background (SGWB). The targets are grouped in three categories (highest priority, high priority, additional priority), based on their detection potential with Advanced Detectors. There is no additional ranking within each category in this table. Critical for accomplishing these science priorities are the detector characterization, calibration and injection activities described in this document.

** Future searches under development, not included in ongoing production computing requests.

1.1 Searches for Generic Transients, or Bursts

The mission of the Burst group is to detect gravitational wave transients, or *bursts*, and gain new information on populations and emission mechanisms of astrophysical objects, as well as to test theories of gravity. Central to the Burst group philosophy is the assumption of minimal information on the source, so that searches for gravitational wave bursts typically do not require a well-known or accurate waveform model and are robust against uncertainties in the gravitational wave signature. Burst searches thus have the potential to see events that other groups cannot. We refer to this as the “eyes wide open" approach.

For example: the complexity of Supernovae makes it difficult to reliably map the dynamics of a core-collapse into a gravitational wave signal. The merger of precessing intermediate-mass black holes ($\geq 100\,\mathrm{M}_{\odot}$) produces gravitational wave transients which appear as short, sub-second bursts in the data. Long gamma-ray bursts could be associated with a gravitational wave transient lasting more than 10 seconds. Since robust models are not available for many plausible sources, we need data analysis methods that are able to detect emission mechanisms that have not been envisioned yet.

The Burst group implements a variety of methods to identify instances of statistically significant excess power, localized in the time-frequency domain. To discriminate between gravitational waves and noise fluctuations, the analysis requires the signal to appear coherently in multiple detectors. The confidence of a candidate event is established by repeating the analysis on many instances of background, obtained by shifting the data from different detectors with non-physical delays. In a few special cases when an accurate signal model is available, such as for cosmic string cusps or neutron star ring-downs, a search can be done using matched filtering with a bank of templates.

Although burst search algorithms are designed to detect a wide range of signals, their tuning and interpretation benefit from considering how they perform for plausible astrophysical signals. Therefore, the group’s science program involves an active collaboration with the theoretical astrophysics, source modeling and numerical relativity communities.

Many gravitational wave burst sources should also be observable in more traditional channels, from Earth-based astronomical data, through sensitive GRB/X-ray satellite detections, to neutrino signals. Knowledge of the time and/or sky position of the astrophysical event producing a gravitational wave burst can be used to increase the sensitivity of a triggered burst search compared to an untriggered, all-sky search, and the association with a known astrophysical event may be critical in establishing our confidence in a gravitational-wave burst detection. Most importantly, joint studies of complementary data enable scientific insight that cannot be accessed through gravitational waves or other messengers alone. Therefore, in addition to searches using only the gravitational wave data, a significant part of the Burst group’s science program involves connecting with other observations and working closely with the astronomy and astrophysics communities.

1. **Highest priority**

   The Burst group is focused on an *eyes wide open* approach to detecting gravitational wave transients. To maximize its discovery potential, the Burst group employs a strategy of multiple searches, overlapping in parameter space to allow for cross-validation of search outputs. Highest priority goals for the analysis of advanced detector data include:

   - a statement on the transient gravitational wave sky, with population studies if we have several detections, a rare-event detection significance if we have one candidate or an upper limit on the rate of gravitational wave bursts if there is no detection;
   - deployment of multiple analyses for cross validation of the all-sky search results, including verifying the significance of any observed events, across a wide parameter space. This is especially

important for events that are not matched to a specific source model;
- the astrophysical interpretation of any detected signals, leveraging signal characterization and parameter estimation;
- a prompt analysis, trigger production and sky localization, to enable the electromagnetic follow-up of gravitational wave transients;
- prompt reports on astrophysically significant events, such as nearby gamma ray bursts, soft gamma repeater hyperflares, galactic supernovae as well as exceptional bursts of low (MeV) or high (GeV–PeV) energy neutrinos;
- a dedicated search for gravitational wave bursts originating from cosmic strings.

2. **High priority**

   The Burst group will extend the parameter space of the all-sky search to include longer duration transients ($\geq 10\,\mathrm{s}$) which may originate from various astrophysical sources such as long gamma-ray bursts. Long-duration burst searches share similar complexities with their short-duration counterparts. Since the long-duration search is not as mature as the short-duration one, multiple analyses will be deployed to cross-validate the results.

   The Burst group will also pursue, with the burst analysis approach, some classes of compact binary coalescence sources that are not well covered by the current waveform template banks. These include intermediate mass binary black holes, binary black holes with eccentric orbits and intermediate mass ratio inspirals.

   Finally, the Burst group will pursue multi-messenger searches for gravitational wave bursts in conjunction with signatures such as generic gamma ray bursts, fast radio transients, low- and high-energy neutrino observations, and electromagnetic observations of nearby core-collapse supernovae. The Burst group will use information on the astrophysical event to reduce the parameter space over which searches must be performed, leading to a reduction in the false alarm rate and, consequently, an improvement in search sensitivities.

3. **Additional Priority**

   Additional priorities include the search for gravitational waves in association with neutron star transients (eg. pulsar glitches, type I X-ray bursts and soft gamma ray repeater flares) and testing alternative theories of gravity with gravitational wave bursts.

Several of these science targets – intermediate mass black hole binaries, GRBs, electromagnetic followup – overlap with the CBC group, and joint teams are working together across the two groups on these targets.

1.2 Searches for Signals from Compact Binary Coalescences

The inspiral and merger of a binary containing stellar-mass compact objects (i.e., neutron stars and black holes) generates gravitational waves which sweep upward in frequency and amplitude through the sensitive band of ground-based gravitational-wave detectors. The highly relativistic speeds and strongly-curved space-times of compact object mergers generate gravitational waves that encode the dynamics of strong-field gravity. With extreme densities of matter completely inaccessible to terrestrial experiments, mergers involving neutron stars hold the key to understanding the equation of state of nuclear matter. Compact object mergers may also explain the origin and distribution of rare heavy elements and reveal the engine powering gamma-ray bursts. Measuring the masses and spins of a population of compact objects in the Universe can help explain how stellar collapse forms neutron stars and black holes.

At design sensitivity, Advanced LIGO will be able to detect binary neutron star (BNS) mergers to an angle-averaged range of ~ 180 Mpc, neutron star–black hole (NSBH) binaries to ~ 450 Mpc, and stellar-mass binary black holes (BBHs) at luminosity distances over 900 Mpc. LIGO and Virgo conduct their searches jointly with a three-detector network that can be used to localize sources on the sky through methods akin to triangulation. A wide variety of electromagnetic counterparts are expected to accompany the gravitational waves from compact object mergers, ranging from radio, through optical to x-rays and gamma-rays. The joint observation of a source by LIGO, Virgo, high-energy satellites, optical, and radio observatories will be a watershed event in astrophysics.

The scientific program of the LSC/Virgo Compact Binary Coalescence (CBC) Group aims to identify gravitational wave signals from compact binary sources in the detector data, measure the waveform parameters, and use detected signals to study the nature of gravity and the astrophysics of nature's most compact objects. This requires accurate modeling of gravitational wave sources to maximize detection rates, and to accurately measure parameters. The CBC group has an active collaboration with the theoretical astrophysics, source modeling and numerical relativity communities to address these challenges.

1. **Highest priority**

   The detection of gravitational waves from compact binary coalescence using the LIGO and Virgo detectors is the main goal of the CBC group. The highest-priority sources are systems containing neutron stars and/or stellar-mass black holes.

   Although a coincident electromagnetic (EM) counterpart is not required to detect gravitational waves from compact binary coalescence, the coincident detection of an EM counterpart with a CBC event would add significant astrophysical information to our discoveries. Therefore, all-sky low-latency (~ 1 minute) CBC searches will provide rapid alerts for GW detections in order to enable observation of e.g., prompt x-ray and optical afterglows as well as to form a first response to gamma-ray bursts. Gamma-ray burst alerts will also trigger a deep, coherent CBC search targeting the GRB sky position, which will complete within ~ 2 hours and will allow us to test directly whether or not compact binary mergers are gamma ray burst progenitors. Low latency analysis activities include the development of low latency analysis pipelines, low-latency data quality assessment, low-latency significance estimation, sky localization for CBC sources, and joint gravitational wave/EM analyses in the advanced detector era.

   Once CBC sources have been detected, a significant amount of astrophysics can be extracted from the observed gravitational waveforms. The first few detections will allow us to make precise measurement of masses and spins to understand the properties of compact objects and their formation and to make accurate measurement of coalescence rates for CBC sources. After many detections we will constrain the neutron star equation of state, test the genuinely strong-field dynamics of space-time - a regime which can only be probed via direct gravitational wave detection - and conduct cosmological studies without the need for a cosmic distance ladder.

Achieving these goals requires LSC/Virgo scientists in the CBC group to prioritize: data quality, search pipeline development, rates and significance measurement, waveform development, and parameter estimation for detected sources.

2. **High priority**

   High priorities include expanding the CBC search for binary black holes beyond stellar mass, e.g. intermediate mass ratio inspirals, intermediate-mass binary black holes and eccentric binaries, which will necessitate the development of new data analysis algorithms and the implementation of associated template waveforms. Additionally, searching for neutron star binaries with significant component spin is also a high priority. Although neutron stars in binary systems have been observed to have small spin, some isolated neutron stars are known to spin significantly. If neutron stars with significant spins do exist in binary systems, then opportunities to detect them could be lost without a dedicated search.

3. **Additional priority**

   Building more accurate noise models for parameter estimation techniques can dramatically mitigate the effects of non-stationary, non-Gaussian noise on the fidelity of parameter inference. It is a priority to conduct a simulation campaign to study improved noise models for parameter estimation.

   The compact binary parameter space searched in higher priorities is not complete. It covers a plausible range of physical parameters based on observation and stellar evolution models with known detection techniques. However, there are other interesting but less plausible parameter spaces which would have a dramatic impact if discovered. Given additional resources, we would consider searching for compact objects below 1 solar mass. It is possible that neutron stars or black holes could exist with masses down to fractions of a solar mass and be in detectable binary systems. Additionally, the higher priority searches do not include template waveforms that take into account orbital precession. Currently, there are no complete methods to search for precessing binaries, however, work is ongoing to develop such a search and with additional resources we would conduct a precessing binary search in the future.

1.3 Searches for Continuous-wave Signals

The LSC/Virgo Continuous Waves (CW) Group aims to measure gravitational wave signals that are long-lived, nearly sinusoidal and extremely weak, believed to be emitted by rapidly rotating neutron stars in our galaxy. These stars can emit gravitational radiation through a variety of mechanisms, including elastic deformations, magnetic deformations, unstable r-mode oscillations, and free precession, all of which operate differently in accreting and non-accreting stars. Long-term simultaneous gravitational wave and electromagnetic observations of a galactic neutron star would support a rich astrophysical research program.

For known pulsars with measured spin frequencies, frequency derivatives and distances, energy conservation allows setting an upper limit on gravitational wave strain amplitude, known as the *spindown* limit, albeit with significant uncertainties due to poorly understood neutron star astrophysics. Previous searches in LIGO and Virgo data have obtained 95% confidence upper limits well below the spindown limits for the Crab and Vela pulsars. As interferometer sensitivities improve in the Advanced Detector Era, several dozen more known pulsars will become spindown-accessible, primarily at spin frequencies below 100 Hz. For suspected neutron stars with unknown spin frequencies, indirect upper limits based on estimated age or on estimated accretion rates can also be derived. Such indirect limits are more optimistic for non-accreting stars, but accreting neutron stars are more likely to be emitting near their limits.

Because there is so much astrophysical uncertainty in continuous gravitational wave emission and because electromagnetic astronomers have detected fewer than 2500 of the O(10^{8-9}) neutron stars believed to populate our galaxy, the CW group has established a broad program to search for gravitational wave emission from five distinct source categories, ordered below by decreasing *a priori* information known about the sources: 1) known pulsars with well measured timing; 2) other known or suspected isolated neutron stars with limited or no timing information; 3) known or suspected binary neutron star systems; 4) unknown isolated stars in any direction; and 5) unknown binary stars in any direction.

This ordering of categories corresponds to ordering by source strain sensitivity. Targeted searches using known ephemerides from radio, X-ray or γ-ray timing measurements can achieve strain sensitivities limited only by the intrinsic detector sensitivity and observation time spans with minimal trials factor corrections. Directed searches using known sky locations but having no *a priori* frequency information (e.g., *Cassiopeia A*) are degraded by trials factors that depend on the band size searched and on the assumed age of the source (which affects the number and range of higher-order spin derivatives to be searched). The sensitivity achievable with all-sky searches is still further limited by the need to make sky-location-dependent corrections for Doppler modulations of detected source frequency due to the Earth's motion (daily rotation and orbital motion). The number of sky points to search to maintain accurate demodulation grows rapidly with coherence time used in the search (time scale over which the signal is assumed to follow a precise phase model). The effect is severe enough to preclude all-sky searches using coherence times equal to the full observation spans of data runs. Adopting semi-coherent summing of data makes the computational problem tractable, but sacrifices additional sensitivity beyond that from the trials factor of exploring a larger parameter space. Directed searches for suspected neutron stars in binary systems with unknown source frequency must make similar sensitivity tradeoffs, and all-sky searches for sources in unknown binary systems define the current extreme in sensitivity tradeoff for tractability.

In the case of known objects, we have identified sources that seem to be the most promising, and should priorities need to be set because of limited resources (labor or computing), those sources will receive the highest priority. With these considerations in mind, the CW group plans a comprehensive search program in the Advanced Detector Era for all of these source categories, with the following priorities:

1. **Highest priority**

    - Targeted searches for the Crab and Vela pulsars and any other stars for which the spindown limit is likely to be beaten to within a factor of two. High-interest stars likely to fall in this category include PSR J0537–6910 and PSRJ1813–1246, among many others, as detector sensitivities improve. These analyses will include searching at the stellar spin frequency and twice that frequency.
    - Directed search for Cassiopeia A which is the youngest known neutron star in the galaxy, but for which the spin frequency is unknown.
    - Directed searches for the X-ray binaries Scorpius X–1, Cygnus X–3, PSR J1751–305 and 4U 1636-536. The first two are especially bright in X-rays, and in the torque-balance model, GW luminosity scales with X-ray luminosity, while there is evidence in the last two objects for sharp X-ray periodicities that may indicate an r-mode oscillation.
    - All-sky searches for unknown isolated stars. These searches necessarily suffer from degraded strain sensitivity relative to what can be achieved in the targeted and directed searches, but they cast a very wide net, offering a reasonable prospect of discovery.

2. **High priority**

    - Targeted searches for known pulsars for which the spindown limit is unlikely to be beaten, according to conventional theory, but which are extreme astrophysical objects of great interest.
    - Directed searches for young supernova remnants other than Cassiopeia A, including Supernova 1987A, for sources near the galactic center, for sources in nearby globular clusters and for unidentified γ-ray sources with pulsar-like spectra.
    - Directed searches for additional X-ray binaries.

3. **Additional priority**

    - All-sky searches for unknown binary stars. Because of the additional unknown orbital parameter space to search, these searches are most computationally demanding and must make the greatest tradeoffs in strain sensitivity for tractability.
    - All-sky searches for unknown isolated stars, using alternative algorithms.

For every type of search, the CW group supports at least two independent methods (pipelines). This redundancy provides greater robustness against incorrect assumptions in signal modeling and against non-optimum handling of instrumental artifacts. The robustness against incorrect signal modeling is especially important for accreting sources, such as Scorpius X–1, where the time span over which the coherence of the signal model can be safely assumed is uncertain. In fact, that time scale is likely to vary in response to fluctuations in accretion rate.

There is some overlap in the CW search space with searches carried out in the Burst and Stochastic working groups. Long-lived transients can be considered to be short-lived CW sources. A small joint subgroup with members from both the CW and Burst groups is carrying out work in this area. CW sources with deterministic but unknown phase evolution, such as from a neutron star in a binary system with uncertain parameters, may be detectable via the “radiometer” method in use by the Stochastic group. Tradeoffs among search methods for such sources are being explored in a joint CW/Stochastic mock data challenge focused on the search for Scorpius X-1.

1.4 Searches for Stochastic Backgrounds

The prime objective of the Stochastic Gravitational Wave Background (SGWB) group is to measure the stochastic background. A stochastic gravitational-wave background is formed from the superposition of many events or processes that are too weak and/or too numerous to be resolved individually, and which therefore combine to produce a stochastic background. A stochastic background can arise from cosmological sources such as inflation, cosmic strings, and pre-Big-Bang models. Alternatively, it can arise from astrophysical sources such as compact binary coalescences, supernovae, and neutron stars.

Comprehensive searches have been carried out using data from initial LIGO and Virgo. No signal was detected, but our results constrain the energy density of the stochastic background to be $\Omega_0 < 5.6 \times 10^{-6}$ at 95% confidence. Advanced detectors are expected to have about $10\times$ better strain sensitivity than the initial detectors, as well as to extend the sensitive band from 40 Hz down to 10 Hz. These improvements and wider bandwidth will enable breakthroughs in searches for the stochastic background, with a potential sensitivity of $\Omega_0 < 6 \times 10^{-10}$. The detection of a cosmological background would be a landmark discovery of enormous importance to the larger physics and astronomy community. Simulations studies show the detection of an astrophysical background is not unlikely, and it would be of great interest as a probe of the evolution of the Universe since the beginning of stellar activity.

The SGWB group has built on the cross-correlation infrastructure, originally designed to carry out searches for isotropic stochastic backgrounds, to diversify and to carry out a wide range of interesting analyses. The SGWB directional search provides a method of distinguishing between different stochastic sources using sky maps of gravitational-wave power; the narrowband radiometer has been used to search for gravitational waves from Scorpius X-1, the Galactic Center, and SN 1987A. The radiometer provides an important tool for gravitational-wave astronomy when there is significant uncertainty in the phase evolution of a neutron star signal (as is the case with the low-mass X-ray binary source, Scorpius X-1). The radiometer limits on Scorpius X-1 from initial LIGO remain the most constraining to date over a portion of the observing band, and the SGWB Group continues to develop the search, in collaboration with the Continuous Waves Group.

The SGWB group has developed a cross-correlation pipeline to search for very long-lived gravitational-wave transients lasting hours to weeks. It may be possible for neutron stars to emit transient gravitational waves on these time scales. Moreover, exotic models allow for the possibility of a seemingly persistent signal to start or stop during an observing run, also leading potentially to very long transient signals. An efficient very-long-transient detection algorithm will have other useful applications: it can establish if an apparently persistent source, e.g., observed in a stochastic background search, exhibits variability in time, and it can be used to understand the behavior of detector artifacts on timescales of days to weeks.

The SGWB group is actively involved in detector characterization efforts. Much of this work has overlap with both the Detector Characterization and SGWB groups. For example, the SGWB group uses Detector Characterization measurements of correlated magnetic noise in order to find solutions that minimize contamination in stochastic searches. Correlated noise, e.g., from Schumann resonances, can create coherence in widely separated detectors, which is possible to mistake for a stochastic background signal, thereby introducing a bias. The group is also developing a stochastic data-quality monitor to track search sensitivity in real time and to identify problematic sources of noise.

1. **Highest priority**

   The highest priorities of the SGWB group are the isotropic search, the directional search, and the search for very long transients. The isotropic analysis is the original *raison d'être* for the SGWB working group, and the detection of a stochastic background is the group's most compelling scientific deliverable. The directional search—which employs both a radiometer algorithm and a spherical harmonic decomposition algorithm—generates sky maps (and strain spectra), which can be used to identify cosmological or local anisotropies as well as point sources. This long-established analysis is an important tool for distinguishing between different sources of the stochastic background (e.g., isotropic signals vs. signals clustered in the galactic plane). While the directional search assesses the contribution to stochastic signals from different directions and from different frequency bins, the search for very long transients assesses the contribution from different times. The three searches together provide a complete understanding of the origin of any observed signal. We carry out a number of activities in support of these three searches including mock data challenges, modeling of different sources of the stochastic background, parameter estimation, folding of data into a sidereal day, detector characterization, and an extension to the isotropic search to look for non-standard polarization modes in the stochastic background.

2. **High priority**

   We designate as high-priority a program to follow up on CBC and burst detection candidates with a low-cost cross-correlation search. The search produces spectrograms showing the detection candidate in cross-correlated data and is designed to provide useful diagnostic tools for visualization and characterization of candidate events. For compact binary coalescence signals in particular, it offers a low-cost, independent verification of detections made by matched-filtering pipelines while filling in potential gaps caused by data-processing corner cases. In addition, this method offers a useful visualization of the GW signal in spectrograms.

3. **Additional priority**

   Additional priorities for the SGWB Group includes studies that are at a less mature stage than those listed above, such as measurements of non-Gaussianity of the stochastic background and a search for r-modes from neutron stars.

There is overlap in the SGWB group's search for very long-lived transients with searches being carried out in the Burst and Continuous Wave search groups. Continuous wave sources with deterministic but unknown phase evolution, such as from a neutron star in a binary system with uncertain parameters, may be detectable via the radiometer method in use by the SGWB group, or methods being developed in the continuous wave search group. Trade-offs among search methods for such sources are being explored in a joint Continuous Wave/Stochastic mock data challenge focused on the search for Scorpius X-1.

1.5 Characterization of the Detectors and their Data

Virgo

Noise mitigation, spectral lines identification, glitch reduction and data quality vetoes are the main tasks of the Virgo detector characterization group. Responsibilities include working with the commissioning team to track down any limitation to the detector's sensitivity, working with the calibration team to maintain the calibration and timing accuracy to an acceptable level for GW searches, and providing noise information and vetoes to the data analysis groups and commissioning team. During past science runs and commissioning periods, the Virgo detector characterization team has provided several investigation and monitoring tools, and data quality vetoes which impacted positively both commissioning activity and astrophysical searches.

Search Data Quality: A new Virgo data quality model has been developed and is currently implemented. This model defines workflows and procedures the group will follow to provide data quality products to searches. In particular, emphasis is made to produce and deliver search-specific data quality vetoes. On top of this, a new and ambitious online architecture is being implemented to provide vetoes to online search pipelines. We have developed with LIGO a common data quality segment database, to benefit Burst and CBC groups. It has been moved to production. Additional data quality needs specific to CW and Stochastic search groups include the identification of noise source contributions to spectral lines or non stationary and non linear features. For this, we use automatic spectral lines identification tools already well tested, and a line database.

Early AdvVirgo Characterization: The Virgo detector characterization team will begin noise and glitch studies on each commissioned sub-system as soon as they come online, in close collaboration with sub-system hardware coordinators and commissioners. A system of shifts has been organized. Periodically, a team of two shifters is on watch. They study transient and spectral noise using analysis tools developed by the group.

1. **Highest priority**
   The highest priority of the Virgo Detector Characterization is to find and mitigate the sources of noise and to provide data quality information to the LSC-Virgo search groups in order to reduce the impact of the remaining noises.

2. **High priority**
   Our current high priorities are the development of useful tools for commissioning and an early characterization of each sub-system of Advanced Virgo in order to reduce the need of vetoes in future searches. This will imply a coherent system of monitoring web pages, a spectral line database catalogue, identification of non stationary lines and a software infrastructure to provide useful online data quality information.

3. **Additional priority**
   Additional priorities for Virgo detector characterization are to develop improved methods to uncover the paths and the sources of the noise transients which most impact the searches, and to implement automated noise classification tools.

1.6 Data Calibration

LIGO

Calibration of the LIGO interferometer data is critical to the success of the searches and to the confidence in their results. This is a complex task that involves instrumental hardware measurements, detector modeling, computer programs, and extensive validation and review. Calibration is provided both in the frequency domain, as a frequency-indexed response function to be applied to the Fourier transform of the gravitational wave channel, and in the time-domain, as a derived digital time series representing strain as a function of time. The time domain calibrated data, along with an accompanying error budget, is the main calibration product. Early aLIGO critical calibration activities include:

- measurements of instrument transfer functions and calibration model parameters,
- development and improvement of instrumental measurements,
- estimation and reduction of the errors in the calibration data products,
- deployment and use of the photon calibrator as an independent cross-check of the calibration,
- development and improvement of time-domain data generation techniques, including use of gstlal and the aLIGO front-end system,
- development of pre-processed h(t) products, such as whitened, cleaned, and coherent data streams,
- development of on-line tools to monitor calibrated data quality, and
- a comprehensive review of entire calibration procedure.

The scope of the calibration team includes the timing of LIGO data. Traceable and closely monitored timing performance of the detectors is mission critical for reliable interferometer operation, astrophysical data analysis and discoveries. Critical timing tasks include:

- developing of injection techniques to determine accurate timing through direct test mass excitations,
- expanding the capabilities of data monitoring tools related to timing and phase calibration,
- enhancing the availability of timing diagnostics for various subsystems,
- measuring and documenting the timing performance of critical digital subsystems,
- measuring and documenting the end to end timing and phase calibration measurements of the detectors (e.g., through the photon calibrator, characterization of analog modules, etc.), and
- reviewing the physical/software implementation and documentation of the timing components of critical subsystems.

Virgo

During the Virgo science runs, the calibration measurements have been automated and extended to have some redundant data. It includes measurement of the absolute time of the Virgo data, measurement of the transfer function of the dark fringe photodiode readout electronics, measurement of the mirror and marionette actuation transfer functions and monitoring of the finesse of the arm cavities. The calibration output are then used (i) in the frequency-domain calibration, resulting in the Virgo sensitivity curve, (ii) in the time-domain calibration, resulting in the h(t) strain digital time series and (iii) for the hardware injections. Independent cross-check of the reconstruction has been done systematically during VSR4 using a photon calibrator.

The methods used for Virgo will still apply for AdV after some tuning for the new configuration. Simulations have been carried on for the a priori most challenging measurements, i.e. the measurement of the mirror actuation response. They confirm that the Virgo methods can still be applied, putting some constraints on the minimum force to be applied on the AdV arm mirrors. In parallel a conceptual design of the new photon calibrator to be developed for AdV is being finalized before the setup is built and then installed in 2015. Critical calibration activities are:

- development and improvement of instrumental measurements (in particular with the digital demodulation electronics of the photodiode readout),
- prototyping and installation of a photon calibrator,
- development of online tools to monitor the Virgo timing permanently,
- upgrade the h(t) reconstruction method after the study of the impact of some parameters that were neglected during the Virgo era.

1.7 Hardware Injections

Hardware injections are simulated gravitational wave signals added to LIGO and Virgo strain data by physically actuating on the test masses. They provide an end-to-end validation of our ability to detect gravitational waves: from the detector, through data analysis pipelines, to the interpretation of results. The hardware injection group is tasked with the development, testing, and maintenance of hardware injection infrastructure. This includes on-site software to carry out the injections at specified times. We also work with the search groups to maintain the software that generates gravitational waveforms suitable for injection.

Each data analysis group works with the hardware injection team, in different ways: Burst and CBC groups provide transient waveforms and determine suitable injection rates, the CW group selects the parameters for neutron star signals, which persist throughout the science run, and the SGWB group typically carries out one or two ≈ 10 min injections during each science run. The search groups analyze hardware injections during science and engineering runs to identify and solve problems as they come up, and the results of these studies are reported back to the hardware injection team so that adjustments can be made.

While most injections are known to the LSC, there are also blind injections, for a blind test of the analysis. Although blind injections are performed by a separate team, the hardware injection group is in charge of maintaining the blind injection infrastructure, nearly identical to the regular injection one, and provides training.